

# PAPER OUTLINE

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## **Studies of particle flow using calorimeter clusters in $pp$ collisions at 900 GeV and 7 TeV with the ATLAS detector at the LHC**

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### **Abstract**

We present first measurements of particle flow correlations in  $pp$  collisions using the ATLAS calorimeters. Data were collected in 2009 and 2010 using proton-proton collisions at a center of mass energy of 900 GeV and 7 TeV. A minimum bias trigger which required a charged particle in scintillation counters on either side of the interaction point was used. Particle flows are measured using clusters of energy in the ATLAS calorimeters, taking advantage of their fine granularity. The results on the angular correlation between clusters and the correlation between the mean cluster momentum and the number of clusters are presented. The results are compared to Monte Carlo predictions and provide an independent measurement to that obtained using charged particles.

# 1 Introduction

Many physics processes to be studied at ATLAS require precision measurements of jets and missing transverse energy obtained from the calorimeter system. An important and unavoidable background to these measurements comes from the so-called underlying event, which represents the soft part of the proton-proton interaction and which must be modeled using phenomenological models in Monte Carlo (MC) generators. Such models must be tuned to experimental data and heretofore this tuning has been carried out using only charged particles. We use the fine granularity of the ATLAS calorimeter to allow the definition of clusters of energy (termed topoclusters in the remainder of this paper) and show using Monte Carlo simulation that the number of topoclusters is strongly correlated with the number of stable particles produced in the interaction. As is the case for charged particles, the number density of topoclusters and the average topocluster transverse energy are powerful observables. These are compared to MC predictions from phenomenological models and provide new characteristics which may be used to tune them.

As first noted elsewhere [1] we extend this measurement by looking at cluster particle densities in regions which are most sensitive to the physics of the underlying event. The measurement is performed in three regions of phase space, as shown in Figure 1 where the "transverse" region is the region which is considered to be the most affected by the soft QCD processes responsible for the underlying events.

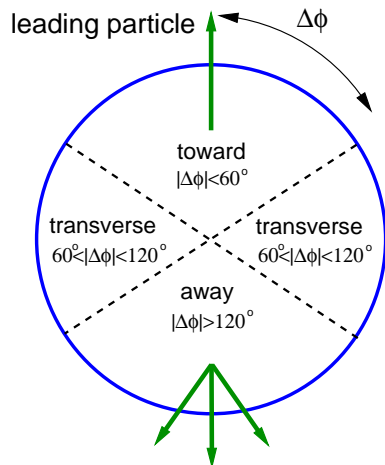


Figure 1: A schematic representation of several phase-space regions used for studies in this note

The analysis using topoclusters energy has several important features. Firstly, it provides a means to be sensitive to the entire hadronic final state (including neutral hadrons). Secondly, the analysis is complementary to the corresponding analysis using charged particles but with completely independent systematics. Finally, jet reconstruction is based almost entirely on energy deposition in the calorimeter and this analysis of the underlying event can be used directly to estimate the effect of underlying event on the jet energy measurement.

## 2 The ATLAS Detector

A description of the ATLAS detector, with the emphasis on the calorimeter.

### 3 Data selection and MC samples

The 900 GeV data used in this analysis were collected during 2009, between December 6 and 15. A total of 455,590 events were collected from colliding proton bunches in which the MBTS\_1 trigger recorded one or more hits on either side of the calorimeter.

The events to be analyzed were selected using an identical procedure as described in [2]. In a similar approach to that presented in [2], only clusters with  $p_T > 0.5$  GeV and  $|\eta| < 2.5$ <sup>1</sup> are considered.

For the corrections, the truth particles are selected if their lifetime  $\tau$  are smaller than  $3 \cdot 10^{-10}$  seconds. Neutrinos are excluded from consideration. According to this definition,  $K_0^S$ 's,  $\Lambda$ 's and  $\Sigma^\pm$  are treated as stable particles.

The 7 TeV data used in this analysis are collected during 2010. This corresponds to an integrated luminosity of about  $238 \mu b^{-1}$ . A total of about 6M events were collected from colliding proton bunches in which the MBTS\_1 trigger recorded one or more hits on either side of the calorimeter.

### 4 Topocluster properties

Discuss the position and energy measurements. Show correlation plot for the number of topoclusters as a function of track multiplicity (data vs MC).

**Fig. 1 caption:** Correlation between multiplicities of calibrated topocluster and primary tracks in data and PYTHIA MinBias events at a centre of mass energy of 900 GeV.

**Fig. 2 caption:**  $E/p$  as a function of  $P$  in different  $\eta$  bins for isolated tracks topoclusters matched to charged tracks in  $pp$  minimum bias events at a center of mass energy of 900 GeV. The clusters were selected after the local hadronic calibration.

### 5 Measured observables

As for earlier analyses [3, 4], we will study the particle density as a function of the  $p_T$  of the leading cluster in the event. The cluster  $p_T$  was calculated using the calibrated energy scale (hadronic scale). A comparison will be performed with the PYTHIA model after an unfolding procedure for several tunes (MC09, Perugia0, DW).

The density per unit of rapidity is defined as

$$\frac{N}{(\eta_{max} - \eta_{min})} \frac{1}{N_{ev} \delta\phi},$$

where  $N$  is the number of entries in the  $\delta\phi$  bin of the size 0.16 rad and  $\eta_{max} - \eta_{min} = 5$  represents the full pseudorapidity range and  $N_{ev}$  is the number of events triggered by a cluster with  $p_T$  above some value.

In addition, the normalized density distributions will be calculated as:

$$\frac{N}{(\eta_{max} - \eta_{min})} \frac{1}{N_{ev} \Delta\phi},$$

where  $N$  is the number of entries in bins of  $p_T(lead)$ ,  $N_{ev}$  is the number of events, and  $\Delta\phi$  is the range in  $\phi$ . In the case of the toward, away and transverse regions,  $\Delta\phi = 0.33$  rad.

Finally, the average  $p_T$  of topoclusters will be measured as a function of  $\Delta\phi$  and  $p_T(lead)$ .

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<sup>1</sup>  $E_T >$  and  $p_T$  are respectively the cluster energy and momentum transverse to the beam direction.

## 6 Uncorrected distributions and correction procedure

Due to the complexity of the measured variables, a bin-by-bin correction procedure is used to unfold the observed distributions to the hadron level. The correction factors

$$C = \frac{\mathcal{A}^{\text{gen}}}{\mathcal{A}^{\text{det}}},$$

are evaluated separately for each observable. In the above expression,  $\mathcal{A}^{\text{gen}}$  is calculated at the generator-level of PYTHIA MC09 and  $\mathcal{A}^{\text{det}}$  is that at the detector-level of this model. The corrected value for an observable is found by multiplying its measured value by the relevant correction factor. The correction factors thus unfold the data to the hadron level and include corrections for event selection, efficiency, purity, bin-by-bin migration, and smearing of the distributions when the leading particle is misidentified and the second leading cluster is used to set the energy scale. In the latter case, this leads a smearing of particle densities.

Contributions from single and double diffraction will be discussed using PYTHIA 6 and PHOJET.

## 7 Systematics

The systematic uncertainties on the measured densities were determined by changing the selection cuts or the analysis procedure and repeating the analysis. The following systematic studies have been carried out, with a typical resulting uncertainty for the given in parentheses:

- The largest systematic uncertainty comes from the energy scale of calibrated topoclusters (5%).  
For electromagnetic (trackless) topoclusters at  $p_T > 500$  MeV, the energy scale uncertainty is +1% will be discussed. This uncertainty was also included.  
The energy scale uncertainty discussed above is significantly larger than the uncertainty of the event selection (including the trigger selection of the minimum bias events) [2];
- Positions of topocluster centers in  $\eta$  and  $\phi$  were shifted by the size of one cell (0.025 rad) in the LArg calorimeter;
- The uncertainty related to the electronic noise which may not be well described by MC.
- The bin-by-bin corrections were estimated using a MC with an extra 10% material in front of the tracking system. The extra material decreases the efficiencies and thus increases the bin-by-bin correction factor.
- A model dependence of the bin-by-bin corrections will be estimated using the alternative Perugia0 tune.

The overall systematic uncertainty will be determined by adding the above uncertainties in quadrature.

## 8 Results

In this section, the final results obtained after the detector corrections are discussed. Only distributions which have the smallest bin-by-bin correction factors have been used for the final measurements.

**Fig. 3(a) caption:** The density of particles per unit of pseudorapidity as a function of the distance in  $\phi$  between the leading particle and other particles in an event.

**Fig. 3(b) caption:** Same as the previous figure for 7 TeV.

**Fig. 4(a) caption:** The average transverse momenta of particles as a function of the distance in  $\phi$  between the leading particle and other particles in an event for 900 GeV data.

**Fig. 4(b) caption:** Same as the previous figure for 7 TeV.

**Fig. 5 caption:** The average number of particles per event in one unit interval in  $\eta$  and  $\phi$  as a function of the  $p_T(lead)$  for the transverse region. 900 GeV and 7 TeV data are shown on the same plot.

**Fig. 6 caption:** The average transverse momenta of particles as a function of the  $p_T(lead)$  for the transverse region. 900 GeV and 7 TeV data are shown on the same plot.

**Fig. 7 caption:** The average transverse momenta of particles as a function of particle multiplicity for different regions. 900 GeV and 7 TeV data are shown on the same plot.

## 9 Summary

In this note, density and the average transverse spectra are studied and compared with the PYTHIA predictions with different tunes. All predictions fail to describe well the density distribution as a function of the azimuthal angle between the leading charged particle and any other particle in an event.

Different PYTHIA tunes fail in different extent. All Monte Carlo predictions fail to describe the particle densities as a function of  $\delta\phi$ . For the average transverse momentum as a function of  $\delta\phi$ , a good agreement is observed for PYTHIA MC09 tune, while Perugia0 and DW turn to underestimate the data.

The above conclusion quantitatively agrees with that for charged particles [3, 4]. and provides a systematically independent measurement to that obtained using tracks.

## 10 Supporting material

A supporting material for this article is linked to

<https://twiki.cern.ch/twiki/bin/view/AtlasProtected/TopoClustersUE>.

This page contains talks, ATLAS notes, figures and ROOT files.

COMM-to-INT ATL-COM-PHYS-2010-210 note:

<http://cdsweb.cern.ch/record/1262602>

## References

- [1] The CDF Collaboration, *Underlying event in hard interactions at the Fermilab Tevatron  $p p$  collider*, Phys. Rev. D **70** (2004) .
- [2] The ATLAS Collaboration, *Charged-particle multiplicities in  $pp$  interactions at  $\sqrt{s}=900$  GeV measured with the ATLAS detector at the LHC*, arXiv:1003.3124 (2010) .
- [3] The ATLAS Collaboration, A. Buckley et al., *Track-based underlying event measurements in  $pp$  collisions at  $\sqrt{s} = 900$  GeV with the ATLAS detector at the LHC*, ATL-COM-PHYS-2010-164 (2010) .
- [4] The ATLAS Collaboration, A. Buckley et al., *Using bin-by-bin corrections for track-based underlying event measurements in  $pp$  collisions at 900 GeV*, ATL-COM-PHYS-2010-165 (2010) .